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A Survey of Human Factors Methodologies and Models for Improving the Maintainability Design of Emerging Army Aviation Systems

John W. Ruffner
Anacapa Sciences, Inc.

February 1990

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This report presents the findings of a literature review conducted to identify human factors methods and models that might be used to improve the maintainability of emerging Army aviation systems. Three methods and seven models are reviewed. The three methods are Logistic Support Analysis, Hardware versus Manpower, and Acquisition of Supportable Systems Evaluation Technology. The seven models are the Human Operator Simulator, Microcomputer Systems Analysis of Integrated Networks of Tasks, Sequiturs Workload Analysis System, Task Analysis and Workload, Maintenance Personnel Performance Simulation, Crew Chief, and Profile. A comparison of the methods and models suggests that the Crew Chief and Profile models have the greatest immediate use for improving maintainability design. It is recommended that research be initiated that will (a) evaluate the Crew Chief and Profile models to see if they can be applied to the maintainability design of Army aviation systems; (b) investigate ways in which the other models might be modified and applied to Army aviation maintainer tasks; and (c) begin a program of maintainability research to address Army aviation systems, mission requirements, and operational environments.

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A Survey of Human Factors Methodologies and Models for Improving the Maintainability Design of Emerging Army Aviation Systems

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Human Factors in Training
and Operational Effectiveness

FOREWORD

The Army Research Institute Aviation Research and Development Activity (ARIARDA) at Fort Rucker, Alabama, is an operational unit of the Army Research Institute for the Behavioral and Social Sciences (ARI) Systems Research Laboratory and provides research support in aircrew training to the U.S. Army Aviation Center. Research is conducted in-house and is augmented by onsite contract support as required. This report documents contract work performed by ARIARDA to support the U.S. Army Aviation Systems Command (AVSCOM) at St. Louis, Missouri. The work was performed under the Memorandum of Understanding between AVSCOM and ARI, dated 10 April 1985.

One of the primary objectives of the Army's Manpower and Personnel Integration (MANPRINT) program is to influence the design of military systems so that they can be operated and maintained in the most cost-effective and safest manner. Although progress has been made in designing Army aviation systems compatible with the capabilities and limitations of operators, little attention has been paid to designing systems that are compatible with the capabilities and limitations of Army maintainers. Methods and models are needed to improve the maintainability design of aviation systems early in their development.

This report presents the findings of a literature survey of human factors methods and models that might be applied during the early stages of system development to improve the maintainability design of emerging Army aviation systems. The survey supports the Army's MANPRINT program. Once the methods and models with the greatest potential are identified, it will be possible to evaluate them through follow-on research.

The results of this research have been briefed to the Director, Systems Research Laboratory, ARI, and to the Deputy to the Assistant Deputy Chief of Staff for Personnel, U.S. Army MANPRINT Directorate, on 23 March 1989. The results will be used by AVSCOM to support the selection of a methodology or model for improving maintainability design.

Edgar M. Johnson

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Technical Director

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The author wishes to express his appreciation to everyone who provided the reference material necessary to conduct the literature review. Special thanks are expressed to the members of the Anacapa Sciences, Inc., staff who reviewed and critiqued several earlier versions of this report and to Ms. Nadine McCollim for her typing support.

A SURVEY OF HUMAN FACTORS METHODOLOGIES AND MODELS FOR IMPROVING THE MAINTAINABILITY DESIGN OF EMERGING ARMY AVIATION SYSTEMS

EXECUTIVE SUMMARY

Requirement:

Increasingly complex aviation systems are being developed to enhance the ability of Army aviators to fly, fight, and survive on the modern battlefield. In the past, these systems often were designed with inadequate regard for the mental and physical capabilities and limitations of the soldiers available to operate and maintain them. In response to the Army's Manpower and Personnel Integration (MANPRINT) initiative, several methodologies and models have been developed or modified recently for applying knowledge about human capabilities and limitations to improve the design of emerging systems. However, the majority of this work has been directed toward the system operator rather than the system maintainer.

At the request of the Army Research Institute Aviation Research and Development Activity (ARIARDA), Anacapa Sciences researchers reviewed the literature to identify human factors[1] methodologies and models that might be used to improve the maintainability of emerging Army aviation systems. This report presents the findings of the literature review.

Procedure:

A literature review was conducted on the topics of (a) maintenance, (b) maintainability design, (c) comparability methodologies, and (d) operator and maintainer behavioral simulation models. The review began with a search of (a) the National Technical Information Service data base, (b) the Defense Technical Information Center data base, and (c) the cumulative indexes for selected scientific publications. Approximately 130 relevant documents were identified and reviewed. The documents reviewed include (a) human factors engineering and maintainability engineering textbooks; (b) maintainability design guidelines; (c) other maintainability literature reviews; (d) technical reports; (e) journal articles; (f) papers presented at professional meetings; (g) military standards and handbooks; and (h) Army regulations, field manuals, and technical manuals.

[1]The term "human factors" is used in this report in its broadest sense. Unless otherwise specified, the term encompasses all six MANPRINT domains (i.e., Manpower, Personnel, Training, Human Factors Engineering, System Safety, and Health Hazards).

Ninety-nine of the documents reviewed are cited in this report. Forty-five documents describe system and equipment maintenance and work directed toward improving system and equipment maintainability. Nine documents describe comparability methodologies, 18 documents describe operator models, and 6 documents describe maintainer models. The remaining 21 documents address MANPRINT issues and system design requirements.

Findings:

To provide a basis for evaluating the methodologies and models, the report presents a brief overview of aviation maintenance and the research performed to improve maintainer performance and maintainability design. Most of the research identified during the literature review was performed or sponsored by the U.S. Air Force or the U.S. Navy.

Three comparability methodologies and seven behavioral simulation models that were judged to have utility for improving the maintainability design of emerging Army aviation systems were identified during the literature review and are discussed in this report. The three comparability methodologies reviewed are:

- Logistic Support Analysis (LSA),
- Hardware versus Manpower (HARDMAN), and
- Acquisition of Supportable Systems Evaluation Technology (ASSET).

The seven computer simulation models reviewed are:

- Human Operator Simulator (HOS),
- Microcomputer Systems Analysis of Integrated Networks of Tasks (Micro-SAINT),
- Sequiturs Workload Analysis System (SWAS),
- Task Analysis and Workload (TAWL),
- Maintenance Personnel Performance Simulation (MAPPS),
- Crew Chief, and
- Profile.

The HOS, Micro-SAINT, SWAS, and TAWL models were developed to model operator performance. The MAPPS, Crew Chief, and Profile models were developed to model maintainer performance. Current exploratory research directed toward the development of computer models that combine expert system and computer-aided design (CAD)

techniques to improve maintainability design during the systems engineering process also are discussed.

All of the methodologies and models reviewed were judged to have some utility for improving the maintainability design of emerging Army aviation systems. However, the utility of the comparability methodologies and operator models is limited. The utility of the comparability methodologies is limited because they produce little direct insight about design changes required to improve maintainability, tend to perpetuate poor maintainability design features and personnel practices, rely extensively on expert judgment, and are very time consuming and labor intensive.

The utility of the operator models is limited because they do not account for many of the characteristics that distinguish system maintenance from system operation. In addition, each of the models has specific deficiencies that limit utility for simulating maintainer performance. Therefore, it is inappropriate to use the operator models, in their present forms, to simulate maintenance performance and to predict maintainer workload.

The MAPPS model was developed to simulate maintainer performance in the nuclear power plant environment. The extent to which the MAPPS model may be useful for improving the maintainability design of emerging aviation systems depends on the similarity between maintenance tasks and working conditions in a nuclear power plant and those in an Army aviation maintenance environment. The HOS, Micro-SAINT, SWAS, TAWL, and MAPPS models will require extensive modifications to be applied to Army aviation maintainer tasks.

The Crew Chief and Profile models were developed to simulate maintainer performance of the two types of activities that require the majority of maintainers' time: (a) accessing, removing, and replacing equipment, and (b) fault detection and troubleshooting. Of the methodologies and models reviewed, Crew Chief and Profile were judged to have the greatest potential for improving the maintainability design of emerging Army aviation systems.

The literature review failed to reveal a comprehensive methodology or model of maintainer performance and workload that can be used to predict maintainability during the early stages of Army aviation system development. One reason for this shortcoming is the lack of a validated set of criteria to guide the development of the methodology or model and to use in evaluating the methodology's or model's utility. Ten criteria, drawn from the maintenance and maintainability design literature, are proposed for this purpose.

Utilization of Findings:

The Crew Chief and Profile models should be evaluated to determine their utility for improving the maintainability design of Army aviation systems. The HOS, Micro-SAINT, SWAS, TAWL, and MAPPS models also should be evaluated to determine the desirability and feasibility of modifying them to simulate the performance of maintainer tasks not addressed adequately by either the Crew Chief or Profile models and to predict maintainer workload.

A SURVEY OF HUMAN FACTORS METHODOLOGIES AND MODELS FOR IMPROVING THE MAINTAINABILITY DESIGN OF EMERGING ARMY AVIATION SYSTEMS

CONTENTS

Page

LIST OF TABLES

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AH	-	Attack Helicopter
AI	-	Artificial Intelligence
AR	-	Army Regulation
ARI	-	Army Research Institute for the Behavioral and Social Sciences
ARIARDA	-	Army Research Institute Aviation Research and Development Activity
ASSET	-	Acquisition of Supportable Systems Evaluation Technology
ATE	-	Automatic Test Equipment
AVIM	-	Aviation Intermediate Maintenance
AVSCOM	-	Aviation Systems Command
AVUM	-	Aviation Unit Maintenance
BITE	-	Built-In Test Equipment
CAD	-	Computer-Aided Design
CH	-	Cargo Helicopter
COMBIMAN	-	Computerized Biomechanical Man Model
FM	-	Field Manual
HARDMAN	-	Hardware versus Manpower
HOS	-	Human Operator Simulator
LHX	-	Light Helicopter Experimental
LRU	-	Line Replaceable Unit
LSA	-	Logistic Support Analysis
LSAR	-	Logistic Support Analysis Record
MAC	-	Maintenance Allocation Chart
MANPRINT	-	Manpower and Personnel Integration
MAPPS	-	Maintenance Personnel Performance Simulation
Micro-SAINT	-	Microcomputer Systems Analysis of Integrated Networks of Tasks
MIST	-	Man-Integrated Systems Technology
MTBF	-	Mean-Time-Between-Failure
MTTR	-	Mean-Time-To-Repair
SAINT	-	Systems Analysis of Integrated Networks of Tasks
SWAS	-	Sequiturs Workload Analysis System
TAWL	-	Task Analysis and Workload
UH	-	Utility Helicopter

A SURVEY OF HUMAN FACTORS METHODOLOGIES AND MODELS FOR IMPROVING THE MAINTAINABILITY DESIGN OF EMERGING ARMY AVIATION SYSTEMS

Section I: Introduction

Increasingly complex aviation systems are being developed to enhance the ability of Army aviators to fly, fight, and survive on the modern battlefield. However, these systems are often designed with inadequate regard for the mental and physical capabilities and limitations of the soldiers who will be available to operate and maintain them (Malone, Heasly, Waldeisen, & Hayes, 1986; Neal, Robinson, Takacs, & Rainwater, 1986; Robinson, Deutsch, & Rogers, 1970). Although some recent progress has been made in designing aviation systems to be compatible with the capabilities and limitations of operators, considerably less progress has been made in designing systems to be compatible with the capabilities and limitations of Army maintenance personnel.

The Maintenance Problem

The term maintenance refers to the activities required to retain an item in or restore it to an operational condition (Department of Defense, 1981). Smith, Westland, and Crawford (1970) reported that the problem of maintaining military equipment in a state of readiness grew to enormous proportions from 1950 to 1970, and that the dominant cause of the maintenance problem was the progressive and rapid increase in equipment complexity. In a recent review, Bond (1987) concluded that the situation had not improved, and that a "persistent maintenance crisis" exists in the military.

Examples of the persistent maintenance crisis abound. Nawrocki (1981) reported that, across all military systems, about 30% of components originally diagnosed as faulty were actually operating correctly; for some equipment the incorrect fault diagnosis rate may have been as high as 60%. Halff (1984) reported that only about one-half of the combat aircraft on a U.S. Navy carrier were able to be flown off the ship with all systems in a ready condition.

Maintenance Personnel Shortage

A chronic shortage of qualified maintenance personnel contributes to the maintenance problem. Potempa, Lintz, and Luckew (1975) noted that it has become extremely costly to recruit and train individuals to the skill levels necessary to maintain modern systems. The current maintenance personnel problems will be exacerbated in future years because of the projected reduction in the number of military-age individuals who will be available for recruitment. Furthermore, the military services will have to

compete with the civilian job market for the most capable individuals. Those who are recruited will probably possess lower skills and aptitudes than current service personnel (Hitchcock, Merriman, Moore, & Field, 1982; Malone et al., 1986; Zimmerman, Butler, Gray, & Rosenberg, 1984).

Attrition further exacerbates the maintenance personnel shortage. A small percentage of military maintenance technicians serve more than a 4-year term of enlistment before they either are promoted to supervisory positions or leave the military services. For example, only 40% of aviation maintenance technicians in the U.S. Army and in the U S. Air Force reenlist after completing their initial 4-year enlistment period (Moore et al., 1987; U.S. Total Army Personnel Command, 1989). This makes it extremely difficult for most maintenance technicians to achieve the skill levels required to maintain modern aviation systems (Smith et al., 1970).

Maintenance Costs

The high costs of maintenance also contribute to the maintenance problem. Each year, approximately 25 - 30% of the annual budget for the Department of Defense is expended for maintenance of military systems. The total maintenance costs for a piece of equipment throughout its life-cycle often exceed its acquisition costs (Christensen & Howard, 1981; Nawrocki, 1981; Rigby & Cooper, 1961). Bond (1987) estimated that maintenance costs often account for the highest percentage of an aviation system's total life-cycle costs.

Design Deficiencies

Another factor that contributes to the maintenance problem is inadequate system and equipment design. Potempa et al. (1975) reported that poor maintainability design was a major contributor to required repair time and critical maintainer errors for the maintenance of U.S. Air Force avionic components. More recently, Deibel (1988) identified 30 design characteristics in the U.S. Air Force's F-16 fighter that significantly increase the required maintenance time.

Approaches to Improving System and Equipment Maintainability

Improving system and equipment maintainability is the most likely solution to the persistent maintenance problem. Maintainability refers to the ability of an item to be retained in or restored to an operational condition (Department of Defense, 1981). Specifically, maintainability refers to the ease with which equipment can be inspected, serviced, repaired, or replaced under specified conditions. A system that is easily maintainable

can be quickly restored to service by maintenance personnel with the skill levels that are likely to be available in the field.

Smith et al. (1970) cite three potential approaches to improving the maintainability of complex systems: (a) improve technician skills through training, (b) improve job performance (e.g., troubleshooting) aids, and (c) improve equipment design. Prior to the mid-1960s, the predominant approach was to provide training for improving technician skills, with a secondary emphasis on providing job performance aids. Little attention was paid to improving equipment design. The three approaches are briefly discussed in the following paragraphs.

Improving Training

Until equipment complexity became overwhelming, training was considered the most effective method of reducing time required for system maintenance (Cunningham & Cox, 1972). However, as Smith et al. (1970) noted, efforts to improve training were unsuccessful in reducing the maintenance problem. Improved training was especially unsuccessful in providing the skills required to troubleshoot and locate malfunctions in electronic equipment, an activity that accounted for more than 60% of corrective maintenance time. Despite improved training programs, many maintenance personnel failed to develop the skills required to maintain the complex equipment. As much as one-third of all equipment malfunctions were being attributed directly to prior poor maintenance or improper application of a maintenance procedure (Rigby & Cooper, 1961; Robinson et al., 1970).

Improving Job Performance Aids

The second approach to improving maintainability is to supply technicians with better job performance aids (e.g., written procedural guides, built-in test equipment [BITE], automatic test equipment [ATE]). As Smith et al. (1970) noted, periodic surveys indicate that improvements in troubleshooting manuals result in negligible increases in maintenance effectiveness. Furthermore, even the most accurate BITE and ATE missed between 5% and 10% of system faults, thus requiring manual troubleshooting (Cunningham & Cox, 1972; Maxion, 1984).

Although designed to speed maintenance and to compensate for lower skill levels in the maintenance force, recent developments in BITE and ATE did not provide a satisfactory solution to the maintenance problem (Coppola, 1984). In spite of, and in certain cases because of BITE and ATE, serious maintenance problems persisted, such as high false alarm rates and the unnecessary removal and replacement of functioning equipment. These problems resulted in excessive maintenance times, wasted maintenance resources, and an increased burden on the logistics support system

(Frederickson, Linquist, & Lehman, 1986). This was particularly true for electronic systems, because they imposed the greatest demands on maintenance resources (Richardson, Keller, Maxion, Polson, & DeJong, 1985). Furthermore, additional maintenance resources were required to maintain the BITE and ATE.

Improving System and Equipment Design

The third approach to improving maintainability is to improve the design of systems and equipment. Smith et al. (1970), Crawford and Altman (1972), Greenman (1975), Potempa et al. (1975), and Robinson et al. (1970) conclude that:

- equipment design is the most important factor contributing to maintainability;
- logistics resources, such as tools and test equipment, facilities, and spare parts are used more effectively when maintainability has been designed into a system from the beginning; and
- data, methods, and models that will provide human factors engineering specifications to design engineers during system development are required to produce truly cost-effective and maintainable systems.

The Department of Defense (1983c) recognized that manpower and personnel shortages will continue to be severe unless the maintainability problem is addressed during the design process as well as through the more traditional approaches of improved training and job performance aids. Current Department of the Army policy requires that maintainability be designed into systems and equipment rather than introduced through post-design modifications suggested by test results, field complaints, or product improvement initiatives (Department of the Army, 1986, 1987a, 1987b).

However, an aviation system's maintainability typically is afforded the lowest priority during the design process, being secondary to performance, weight, cost, and operability. Furthermore, efforts to increase system performance and operability often result in added system complexity, with a concomitant increase in maintenance requirements. By the time maintainability problems are identified, changes for the sake of efficient maintenance are often not feasible (Greenman, 1975; McDaniel & Askren, 1985).

Only about 3% of a system's life-cycle costs are expended during the concept exploration phase of the material acquisition process. However, decisions affecting approximately 70% of the system's total life-cycle costs are made during that early phase (King & Weaver, 1987; Risser & Berger, 1984). Therefore, it is more expedient and economical to improve system maintainability through decisions in the early conceptual and design stages than through design changes later in system development. One of the primary objectives of the Army's Manpower and Personnel

Integration (MANPRINT) program is to influence the design of military systems so that they can be operated and maintained in the most cost-effective and safest manner consistent with the manpower structure, personnel aptitudes and skills, and training resource constraints of the Army (Department of the Army, 1987b).

Need

In response to the Army's MANPRINT initiative, several methodologies and models have been developed or modified for applying knowledge about human capabilities and limitations to the design of military systems (Kaplan, 1987; Malone, Perse, Heasly, & Kirkpatrick, 1988). The majority of this work has been directed toward the role of the human as a system operator rather than as a system maintainer. There is a mounting body of evidence indicating that methodologies and models are needed that can be applied to improve the maintainability design of aviation systems early in their development.

At the request of the Army Research Institute Aviation Research and Development Activity (ARIARDA), Anacapa Sciences, Inc., researchers reviewed the literature to identify human factors[1] methodologies and models that might be applied during the early stages of system development to improve the maintainability design of emerging Army aviation systems. The literature review supports the Army's MANPRINT initiative to integrate manpower, personnel, and training considerations into the design of emerging systems (Department of the Army, 1987b). Once the methodologies and models with the greatest potential are identified, it will be possible to evaluate their appropriateness through follow-on research. This report presents the findings of the literature review.

Literature Reviewed

An extensive review of the literature was conducted on the topics of (a) maintenance, (b) maintainability design, (c) comparability methodologies, and (d) operator and maintainer behavioral simulation models. The review began with a search of (a) the National Technical Information Service data base, (b) the Defense Technical Information Center data base, and (c) the cumulative indexes for selected scientific publications. Approximately 130 relevant documents were reviewed. The documents reviewed include: (a) human factors engineering and maintainability engineering textbooks; (b) maintainability design guidelines; (c) other maintainability literature reviews; (d) technical reports;

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[1]The term "human factors" is used in this report in its broadest sense. Unless otherwise specified, the term encompasses all six MANPRINT domains (i.e., Manpower, Personnal, Training, Human Factors Engineering, System Safety, and Health Hazards).

(e) journal articles; (f) papers presented at professional meetings; (g) military standards and handbooks; and (h) Army regulations, field manuals, and technical manuals.

Ninety-nine of the documents reviewed are cited in this report. The number of documents cited in each of seven general categories is summarized in Table 1. The focus of the literature review was placed on documents describing system and equipment maintenance and research directed toward improving the design of systems and equipment to improve their maintainability. It was considered appropriate to review operator models as well as maintainer models for two reasons. First, more progress has been made in developing, implementing, and evaluating operator models than maintainer models, a fact that is evidenced by the small number of maintainer models available and their generally low level of sophistication. Second, the few maintainer models that have been developed cover limited aspects of maintainer performance (e.g., accessibility, troubleshooting) and do not specifically address maintainer workload and its effect on performance. Accordingly, operator models were reviewed to assess their utility for (a) simulating certain aspects of maintainer performance, and (b) predicting maintainer workload and its effect on maintainer performance.

Table 1

Distribution of Literature Reviewed

Category	Number of Documents Cited
Manpower and Personnel Integration	6
System Design Requirements	15
System and Equipment Maintenance	25
Maintainability Design	20
Comparability Methodologies	9
Operator Models	18
Maintainer Models	6
Total	99

Organization of the Report

This report is organized into four sections. Section I describes the background and purpose of the literature review. Section II presents the results of the literature review that apply to aviation maintenance and maintainability design. Section III discusses three comparability methodologies and seven behavioral simulation models (four operator models and three maintainer models) that were judged to have potential for improving the maintainability design of emerging Army aviation systems. This section also briefly summarizes current exploratory research directed toward the development of computer models that combine expert system and computer-aided design (CAD) techniques to improve maintainability design during the systems engineering process. Section IV discusses and compares the relative utility of the methodologies and models reviewed in Section III for improving maintainability design, proposes a set of criteria that should be met by a methodology or model of Army aviation maintainer performance, and identifies future research needs.

Section II: Maintenance and Maintainability Design

Section II presents a brief overview of topics relevant to aviation maintenance and maintainability design. The objective is to acquaint the reader with the basic concepts and issues that should be addressed by the methodologies and models that will be discussed in Section III. The overview will address the following topics:

- types of maintenance activities,
- organization of Army aviation maintenance,
- measures of maintainability,
- maintainability and reliability,
- maintainability design guidelines,
- maintainability prediction procedures, and
- validation of maintainability design guidelines and prediction procedures.

Types of Maintenance Activities

There are three general types of maintenance activities: (a) servicing, (b) preventive (scheduled) maintenance, and (c) corrective (unscheduled) maintenance. Servicing is performed to keep equipment in operating condition and involves such activities as lubricating, fueling, oiling, and cleaning. Preventive maintenance is performed to retain equipment in a specified condition by providing systematic inspection, detection, and prevention of incipient failures. Corrective maintenance is performed to restore equipment to a specified condition once a failure has occurred. Although the specific corrective maintenance activities will vary from situation to situation, five major sequential steps are typically performed (U.S. Army Materiel Command, 1972):

- recognizing that a malfunction exists,
- localizing faults within the system to a particular piece of equipment,
- isolating faults within the piece of equipment to a specific defective component or part,
- repairing or replacing the defective component or part, and
- checking out the system and returning it to service.

Organization of Army Aviation Maintenance

The Army employs a forward support maintenance concept and organizes its maintenance activities to provide the battlefield commander with the maximum number of safe, mission capable aircraft. Maintenance assets are located as close to the operating force as the tactical situation will allow, rather than being located at a fixed location on the battlefield. Maintenance

activities are accomplished at the lowest organizational level consistent with the tactical situation and the available personnel skills, tools, and parts (Payne, 1988). The objective is to provide fast, continuous, and reliable aviation maintenance support in the highly mobile, integrated battlefield expected in future combat situations (Department of the Army, 1985).

Army aviation maintenance is further organized into three levels that correspond to the nature and degree of difficulty of the maintenance functions required (e.g., install, repair, replace) and the skills of the resident personnel. The three levels are (a) aviation unit maintenance (AVUM), also known as organizational maintenance; (b) aviation intermediate maintenance (AVIM); and (c) depot maintenance. Maintenance functions are assigned to one of these three levels according to the Maintenance Allocation Chart (MAC) for each aircraft. The MAC identifies the tools and equipment required to perform maintenance functions on specific components or assemblies (Department of the Army, 1988).

Organization by level of maintenance is necessary because of the demands for tactical deployment of the equipment; it also provides for efficient use of maintenance personnel with different skills and skill levels. Typically, the least skilled maintenance technicians are assigned to AVUM units; individuals with higher skill levels and more experience are assigned to AVIM units and repair depots. A brief description of the types of activities performed at each maintenance level is presented in the paragraphs that follow. The description is based on material from Field Manual (FM) 1-500 (Department of the Army, 1985) and Army Regulation (AR) 750-1 (Department of the Army, 1988).

Aviation Unit Maintenance

AVUM units perform high frequency maintenance functions that are required to retain the aircraft in or return it to a fully mission capable condition with little downtime. Because of operational requirements, there is a greater need to maintain equipment rapidly at this level compared to the other maintenance levels. AVUM activities include:

- performing preflight, postflight, and daily aircraft inspections;
- performing servicing and preventive maintenance checks; and
- inspecting, lubricating, cleaning, adjusting, and replacing line replaceable units (LRUs).

In general, the majority of maintenance technicians' time in the AVUM units is spent (a) gaining physical access to equipment to perform servicing, preventive maintenance, or corrective maintenance; and (b) detecting, localizing, and isolating faults using BITE, ATE, or manual troubleshooting techniques (Cunningham & Cox,

1972; McDaniel & Askren, 1985; U.S. Air Force Systems Command, 1988).

The AVUM capability normally is located in an aviation platoon and is limited by the amount and complexity of available facilities and ground support equipment, and the availability of critical personnel skills. Maintenance personnel at the unit level normally do not repair modules or components removed from the aircraft. Instead, defective modules or components are either discarded or transported to the AVIM units or depots for repair.

Aviation Intermediate Maintenance

All AVIM units are aircraft maintenance companies. They support AVUM units by repairing selected items that cannot be repaired at the lower level. Maintenance functions typically performed at the AVIM level include inspection, troubleshooting, test, diagnosis, repair, calibration, adjustment, and alignment of aircraft modules and components. AVIM units send unserviceable items to depot facilities when they are beyond their authorized capability, capacity, or authority to repair.

Depot Maintenance

Depot maintenance is typically performed by civilian personnel at a limited number of highly specialized, fixed facilities located away from the operational area. Maintenance functions that do not contribute to sustaining air mobility are assigned to depot maintenance. Depot maintenance functions include overhauling, making major repairs, and painting aircraft.

Implications For Maintainability Design

The design engineer should be concerned primarily with the problems of reducing maintenance time at the AVUM level because of the operational need for rapid maintenance. Therefore, it is important to design systems and equipment so that maintainers with relatively low levels of skill and experience can perform the required maintenance functions and tasks quickly and accurately. However, design features that enhance the performance of maintenance functions and tasks required at the AVIM and depot maintenance levels should not be neglected.

Measures of Maintainability

The most commonly used measure of maintainability is mean-time-to-repair (MTTR). MTTR is generally defined as the average time required for a maintenance technician with a specified skill level to locate and isolate a fault, repair or replace the faulty

unit, and verify that the malfunction has been corrected. MTTR also has been referred to as mean corrective maintenance downtime (Crawford & Altman, 1972).

When measuring maintainability, it is customary to separate actual repair time (i.e., the time spent undergoing inspection, repair, or servicing) from the time required to perform other maintenance related activities (e.g., administrative processing, and waiting for repair parts, ground support equipment, and technical inspectors). Actual repair time is the maintainability measure that can be most influenced by the equipment designer.

As Crawford and Altman (1972) and Christensen and Howard (1981) point out, time data may not always be the best measure of how well a system has been designed for maintainability. Therefore, time should not be the only criterion considered. Although time is relatively easy to measure, it has little diagnostic value to the equipment designer because its sensitivity to specific maintenance design features is unknown. In addition to time, the following measures should be considered (Department of Defense, 1983c; Mahar, Kane, Baerthel, & Levine, 1983; Majoros, 1988; Towne, 1988):

- the number of maintenance personnel and skill levels required;
- the potential for and the type and frequency of maintainer error;
- the probability of fault detection;
- the percentage of faults that can be attributed or isolated to a given equipment level;
- the number of incorrect diagnoses;
- the number of functional parts that are unnecessarily removed; and
- the amount of physical and mental workload.

Most of the maintainability measures that have been developed address requirements to perform corrective maintenance on a system as quickly as possible at the AVUM level. This typically results in maintenance concepts that emphasize replacing faulty modules or components and sending the faulty items to a higher maintenance level for repair. Designers often do not put as much emphasis on features that facilitate (a) servicing and performing preventive maintenance on a system or (b) repairing the modules or components that have been transported to the AVIM units and depots (Cunningham & Cox, 1972).

Maintainability and Reliability

A system characteristic closely related to maintainability is reliability. Reliability is the probability that a system component can perform its intended function for a specified interval

under stated conditions (Department of Defense, 1981). The standard measure of reliability is the mean-time-between-failure (MTBF). Reliability is an important factor in determining the overall supportability of a system because it determines how often maintenance will be required for the components of a system. Reliability and maintainability are both regarded as key factors in the design of affordable and supportable systems (Department of Defense, 1983a).

Maintainability Design Guidelines

Maintainability design guidelines describe equipment design features that reduce the required maintenance time and the probability of errors. Human factors researchers have been developing guidelines for over 30 years (e.g., Cunningham & Cox, 1972; Department of Defense, 1984a; Folley & Altman, 1956; Rigby, Cooper, & Spickard, 1961; Schafer, Benson, & Clausen, 1961; U.S. Army Missile Command, 1963). Table 2 presents a list of guidelines extracted from MIL-STD-1472C, Human Engineering Criteria for Military Systems, Equipment and Facilities (Department of Defense, 1984a). Although there are no universally accepted maintainability design guidelines, those found in MIL-STD-1472C are representative. In addition, MIL-STD-1472C is the document most often cited in requests for proposals for aviation systems. Unfortunately, human factors researchers have not been very successful in convincing engineers to incorporate the guidelines during system design (Meister, 1987).

Applicability To Aviation Systems

The design guidelines provided in MIL-STD-1472C are intended to apply to a wide variety of systems and equipment and therefore are often general, vague, and ambiguous. Mahar et al. (1983) evaluated the appropriateness of the guidelines for aviation systems and cited the following major deficiencies:

- The anthropometric data (e.g., strength, reach) are incomplete or inaccurate for the population of aviation maintenance technicians.
- General aircraft equipment location requirements (e.g., access panels, maintenance servicing points) and inspection features are not covered.
- Many design areas that are related to aircraft maintainability (e.g., rigging, armament, jacking) are excluded.
- Requirements for different aviation hardware subsystems (e.g., flight control, electronics) and for different aviation maintenance levels (e.g., unit, intermediate) are not addressed separately.

Table 2

Examples of Maintainability Design Guidelines

Category	Design Guideline
Accessibility	Structural members of units or chassis shall not prevent access to or removal of items.
Access Openings	All access covers that are not completely removable shall be self-supporting in the open position.
Cases	The proper orientation of an item within its case shall be made obvious, either through design of the case or by means of appropriate labels.
Conductors	Cables shall be routed so as to be readily accessible for inspection and repair.
Connectors	Plugs shall be designed so that it will be impossible to insert a wrong plug into a receptacle.
Covers	It shall be made obvious when a cover is not secured, even though it may be in place.
Failure Indications	Displays shall be provided to indicate when equipment has failed or is not operating within tolerance limits.
Fasteners	Whenever possible, identical screw and bolt heads shall be provided to allow various panels and components to be removed with one type of tool.
Handling	All removable or carried units designed to be removed and replaced shall be provided with handles or other suitable means for grasping, handling, and carrying.
Mounting	Field removable items shall be replaceable by use of nothing more than common hand tools.

Mahar et al. (1983) recommended that the guidelines be further developed to provide adequate coverage of design parameters and a sufficient amount of data to allow trade-offs between alternative design concepts and hardware configurations. They also recommended that the guidelines provide demonstrable quantitative criteria that can be verified during design reviews.

Maintainability Prediction Procedures

Maintainability prediction procedures are techniques for generating estimates of the total repair time of equipment (e.g., mean corrective maintenance time, total downtime) as early as possible in the design process. Maintainability prediction is useful for identifying problems and providing an early assessment of whether the predicted downtime and the required quantity and quality of personnel, tools, and test equipment are consistent with the system's operational requirements (Cunningham & Cox, 1972).

Five recommended maintainability prediction procedures are described in detail in MIL-HDBK-472, Maintainability Prediction (Department of Defense, 1984b). It is beyond the scope of this report to describe the maintainability prediction procedures in detail. Instead, a brief summary of each of the five procedures is presented in Table 3. The Roman numerals in Table 3 match the Roman numerals used to identify the five procedures in MIL-HDBK-472. All five procedures use a set of equations to predict the total time required to maintain a system within a given period of operation. The equations are constructed by weighting the time required to repair the system's components by the frequency, or rate, at which the components are expected to fail. The component repair times are obtained from standard time-motion tables or estimated from comparable systems and system components under similar operational conditions. The failure rates are obtained from engineering reliability data or estimated from comparable systems and system components under similar operational conditions.

The procedures differ with respect to the following five factors:

- the types of systems to which they can be applied (e.g., ships versus airplanes);
- the types of equipment to which they can be applied (e.g., electronic versus mechanical);
- the phases during the design process when they can be applied (e.g., concept evaluation versus demonstration and validation);
- the types of information required (e.g., estimates of elemental maintenance task times, number of replaceable components, number of test points, physical layouts, functional diagrams, tools and test equipment); and

Table 3

Summary of MIL-HDBK-472 Maintainability Prediction Procedures

MIL-HDBK-472 Procedure	Summary
I	Estimates total flightline downtime for airborne electronic and electromechanical systems involving modular replacement. Requires standard elemental task times.
II	Predicts the corrective and preventive maintenance downtime of shipboard and shore electronic equipment and systems. Requires standard elemental task times or user estimates of required manhours.
III	Predicts the mean and maximum corrective and preventive maintenance downtime for Air Force ground electronic equipment. Requires checklists of physical design, personnel, and support factors.
IV	Predicts the mean or total corrective and preventive maintenance downtime of systems and equipment. Requires historical data, subjective evaluation, expert judgment, and selective measurement.
V	Predicts mean-time-to-repair, maximum corrective maintenance time, and mean maintenance manhours per operating hour for avionics and ground and shipboard electronics. Predictions can be made for the unit, intermediate, and depot maintenance levels. Requires standard, elemental task times.

- the output parameters that result from exercising the procedures (e.g., total downtime, mean preventive maintenance time, mean maintenance manhours per repair, mean maintenance manhours per operational hour).

The appropriateness of a particular procedure depends primarily on the type of system and equipment and the amount of information that is available.

Existing maintainability prediction procedures are cumbersome, time consuming, labor intensive, and limited by the accuracy and generalizability of the data obtained from comparable systems or system components. Rapid increases in equipment complexity quickly render the historical maintenance task times required by the procedures obsolete. The prediction procedures are highly dependent on mature design data and therefore have limited utility

during the early conceptual and design stages of system development (Cunningham & Cox, 1972). Furthermore, the procedures do not provide a means for incorporating maintainer capabilities and limitations data into the prediction process.

Validation of Maintainability Design Guidelines and Prediction Procedures

Few attempts have been made to validate maintainability design guidelines or prediction procedures, particularly across qualitatively different types of systems (e.g., fixed wing aircraft versus helicopters) and equipment (e.g., mechanical versus electrical). The available research suggests that:

- the validity of maintainability design guidelines depends on the type of equipment and the ability, experience, and motivation of maintenance technicians (Potempa et al., 1975; Topmiller 1964);
- equipment design factors are better predictors of required maintenance time than are personnel or support factors (Retterer, Griswold, McLaughlin, & Topmiller, 1965);
- the current maintainability prediction procedures are moderately accurate within a very limited range of systems, equipment types, and maintenance technician populations; and
- the accuracy of the prediction procedures depends on the availability of the required data at an appropriate level of detail and assumes that there will be no major changes in maintenance concepts (i.e., how and by whom maintenance is to be performed) after the predictions are made (Cunningham & Cox, 1972; Smith et al., 1970).

Section III: Human Factors Methodologies and Models

Section III describes three comparability methodologies and seven behavioral simulation models (four operator models and three maintainer models) that were selected for review and discussion in this report (see Table 4). Three primary criteria were used for selecting the methodologies and models. First, some aspect of the methodology or model was judged to have potential for improving the maintainability design of emerging Army aviation systems. Second, adequate written documentation that described the methodology or model and its intended applications was available in the open literature during the time the literature review was conducted. Third, an operational version of the methodology or model is available for evaluation by the research and development community and for implementation by the Army. The descriptions of the methodologies and models presented in this report were derived from reviewing available written documentation and not from exercising the methodologies or models.

The first two subsections describe the three comparability methodologies and the seven behavioral simulation models listed in Table 4. For each methodology or model, a brief overview is provided that identifies the sponsoring agency, the methodology or

Table 4

Methodologies and Models Reviewed

<u>Comparability Methodologies</u>

- Logistic Support Analysis (LSA)
- Hardware versus Manpower (HARDMAN)
- Acquisition of Supportable Systems Evaluation Technology (ASSET)

<u>Behavior Simulation Models</u>

- Human Operator Simulator (HOS)
- Microcomputer Systems Analysis of Integrated Networks of Tasks (Micro-SAINT)
- Sequiturs Workload Analysis System (SWAS)
- Task Analysis and Workload (TAWL)
- Maintenance Personnel Performance Simulation (MAPPS)
- Crew Chief
- Profile

model's purpose and general objectives, and hardware and software requirements. Following this is a description of the input data requirements, the major steps or procedures, and the output data for the methodology or model. The third subsection presents a brief discussion of current exploratory research directed toward development of computer models that combine expert system and CAD techniques to improve maintainability design during the systems engineering process.

Comparability Methodologies

A comparability methodology is defined in this report as a structured set of activities that are followed to predict the logistics or human resource requirements (i.e., manpower, personnel, and training) of proposed military systems using data available from comparable predecessor systems or system components. The predicted logistics, manpower, personnel, and training requirements for the proposed system or equipment are important factors that must be considered during design for maintainability. The Logistic Support Analysis (LSA) and the Acquisition of Supportable Systems Evaluation Technology (ASSET) methodologies are primarily concerned with maintainer rather than operator resources. In comparison, the Hardware versus Manpower (HARDMAN) methodology is concerned with both operator and maintainer resources.

The major difference between the comparability methodologies listed in Table 4 and the maintainability prediction procedures reviewed in Section II is that the comparability methodologies were developed to predict logistics and human resource requirements of a system, whereas the maintainability prediction procedures were developed to estimate system repair time. However, both depend on the availability, accuracy, and generalizability of data from comparable predecessor systems.

Logistic Support Analysis (LSA)

Overview. LSA is a comparability methodology developed by the Department of Defense (1983a) for identifying, defining, analyzing, quantifying, and processing logistic support requirements, including maintenance. The general objectives of LSA are (a) to influence hardware design, (b) to establish the most effective support concept, and (c) to define logistic support resource requirements.

Description. Table 5 identifies the five categories of LSA tasks and the activities included within each task category. During the LSA process, the logistic support resource requirements of the system are defined through an integrated analysis of all maintainer functions and tasks to determine task frequencies, task times, and personnel and skill requirements. One of the most

Table 5

Logistics Support Analysis (LSA) Task Categories and Activities

LSA Task Category	Activities
Program Planning and Control	Provide for formal program and review actions.
Mission and Support Systems Definition	Establish supportability objectives and related design goals, thresholds, and constraints through comparisons with existing systems and analyses of supportability, cost, and readiness.
Preparation and Evaluation of Alternatives	Propose the best balance between cost, schedule, performance, and supportability; identify functional requirements for maintenance tasks and trade-offs (e.g., manpower and personnel, maintenance level).
Determination of Logistic Support Resource Requirements	Identify the logistic support resource requirements of the new system in its operational environment(s); develop plans for post-production support; analyze maintenance tasks.
Supportability Assessment	Assure that specified requirements are achieved and deficiencies are corrected.

useful outputs of the LSA process is the Logistic Support Analysis Record (LSAR). The LSAR is a subset of documentation that contains detailed engineering and logistic support requirements data (Department of Defense, 1983b). There are several LSAR output summaries that provide information for a maintenance task analysis and that may be useful for improving maintainability design. Lobel and Mulligan (1980) suggest that the most relevant summaries are the following:

- Maintenance Allocation Summary,
- Personnel and Skill Summary,
- Support and Test Equipment Utilization Summary,
- Special and Common Tool Requirements,
- Maintenance and Operator Task Analysis,
- Failure Mode Effects Analysis, and
- Reliability and Maintainability Summary.

Hardware versus Manpower (HARDMAN)

Overview. The HARDMAN comparability methodology is a structured approach for determining the human resource requirements (i.e., manpower, personnel, and training) during the earliest phases of weapon systems development. HARDMAN was originally developed under U.S. Navy sponsorship, but has recently been modified and applied to predict Army human resource requirements (Risser & Berger, 1984). It is designed primarily to support front-end analyses and is most effectively applied during the concept exploration and the demonstration and validation phases of the materiel acquisition process. An automated version of HARDMAN, HARDMAN II, recently was employed during development of the Army's Forward Area Air Defense System. HARDMAN II was formerly called Man-Integrated Systems Technology (MIST) (Stewert & Shvern, 1988).

The objectives of the HARDMAN methodology are (a) to determine human resource requirements (both operator and maintainer), (b) to identify system characteristics that generate excessive human resource requirements, and (c) to provide the necessary information for conducting trade-offs between manpower, personnel, training, and equipment design during the early stages of the systems acquisition process (Mannle & Risser, 1984). The basic approach of the HARDMAN methodology is comparability analysis; knowledge about similar existing systems or system components is used to project requirements for the proposed systems or system components.

Description. The HARDMAN methodology consists of five major interrelated steps (Zimmerman et al., 1984):

- Establish a consolidated data base consisting of functional descriptions of the proposed system and similar predecessor systems, including the associated inputs, such as hardware reliability, personnel information, costs, and training data.
- Determine the manpower and personnel requirements and skills needed to operate and maintain the system.
- Determine the training requirements likely to be imposed by the proposed system.
- Conduct an impact analysis to establish likely manpower and training shortages and to identify system characteristics that generate high human resource costs.
- Perform a trade-off analysis to alter features of the system (e.g., reliability, accuracy of automated fault diagnosis, manning requirements, skill level requirements) and to reduce or eliminate unreasonable requirements.

Each of these steps requires several judgments about (a) the selection of comparable predecessor systems or system components, (b) the identification and assembly of appropriate data on the predecessor systems, (c) the expected performance of the proposed

system as compared to predecessor systems, and (d) the required personnel skills. Gaps in the supporting data often exist at the early conceptual and design stages of system development. Expert judgment is therefore employed to merge the various pieces of information and to generate comprehensive personnel projections (Zimmerman et al., 1984).

Acquisition of Supportable Systems Evaluation Technology (ASSET)

Overview. The ASSET methodology is a system of analytical procedures and computer models that evaluates human resource requirements for proposed weapon systems throughout the acquisition process (Liberati, Egber, French, & Preidis, 1985). ASSET was developed under the sponsorship of the U.S. Air Force Human Resources Laboratory. The models included in ASSET are hosted on the Control Data Corporation CYBER System, Wright-Patterson Air Force Base, Ohio. The conceptual approach and detailed logic used by ASSET are very similar to that used by HARDMAN.

ASSET was developed to accomplish the following objectives:

- Estimate the human and logistics resources that are required to support and operate the weapon system throughout its life cycle.
- Coordinate the development of training programs and technical manuals to ensure that complete and cost-effective maintenance performance instruction is available when the weapon system is deployed.
- Ensure that supportability and human resource requirements are explicitly considered during the design of the weapon system.

Description. The basic elements of ASSET are eight analytical procedures, eight computer models, and a consolidated data base. The application of ASSET centers around the analytical procedures that are supported by the computer models. One or more of the models may be used to support one or more of the procedures. The consolidated data base provides the data required for the ASSET application. The ASSET procedures and models may be applied together to analyze either a complete weapon system or specific system components.

The ASSET procedures most applicable to maintainability design are the Integrated Task Analysis Procedure, the Maintenance Action Network Procedure, and the Design Option Decision Tree Procedure. The Integrated Task Analysis Procedure outlines the requirements for tasks that must be performed to operate and maintain a weapon system. To apply this procedure, the weapon system hardware components are listed and described at the level of specificity that accounts for all of the maintenance tasks that must be performed. Subsequently, hardware elements and maintenance task steps are identified and verified, cues and

accompanying responses for each maintenance step are described, tools and equipment used to accomplish maintenance tasks are listed, and safety hazards and environmental factors related to the maintenance tasks are evaluated.

The Maintenance Action Network Procedure is used to depict the maintenance flow of a weapon system and to define the input data used in the application of ASSET. The Maintenance Action Network uses an event tree structure to describe the maintenance resources required to restore a weapon system to operational readiness. The network identifies the possible maintenance outcomes associated with each subsystem or component failure. Other ASSET models can use this information to compute the total maintenance demand and the requirement for support resources (e.g., crew size, skill categories, skill levels, support equipment, and average time required to complete the tasks associated with the event).

The Design Option Decision Tree Procedure is a graphic procedure for depicting the sequence of engineering decisions required to resolve a design problem. The procedure describes the design options available at each decision point (Askren & Korkan, 1974). This procedure may be used to assess the maintainability as well as the performance, operability, and supportability of a weapon system. Examples of factors that influence the decision options are performance requirements, logistics, weight, cost, reliability, and development risk. In addition, the following types of human resources data can be added:

- the skill levels of personnel required to perform troubleshooting on the equipment,
- the job speciality of the maintenance personnel,
- the time to troubleshoot a failure on the equipment,
- the ease of maintaining the equipment, and
- the complexity of the required tools.

The three procedures described above are supported by the Reliability and Maintainability Model. This model provides information that enables the system designer to identify high support resource consumption areas in which system design efforts can reduce costs. The model defines a measure of support resource requirements, evaluates this measure for each system component, and then ranks each system component accordingly. This identifies the relative impact of each component on support requirements and focuses the designer's attention on potential problem areas.

When the ASSET methodology is exercised for a baseline or alternative system, design features that are high consumers of manpower, personnel, and logistic support resources can be identified. This allows the user to compare the cost and resource requirements of alternative configurations. The application of ASSET to a developing weapon system permits and encourages the early integration of design, logistic support, and operational

concepts so that their combined influence may result in a cost-effective, supportable system.

Behavioral Simulation Models

A behavioral simulation model is defined in this report as a representation of behavior and the influence of behavior on real world events that allows simulated control of the real world events and subsequent prediction of their effects on behavior (Siegel & Wolf, 1981). Behavior simulation models attempt to represent operator or maintainer behavior statistically within the system under study and produce measures of human-system performance effectiveness (Lysaght et al., 1988). Because of the requirements to perform a large number of calculations quickly and to implement logical decision rules, behavioral simulation models are usually implemented on a digital computer.

The Human Operator Simulator (HOS), Microcomputer Systems Analysis of Integrated Networks of Tasks (Micro-SAINT), Sequiturs Workload Analysis System (SWAS), and Task Analysis and Workload (TAWL) models were developed specifically to model operator tasks. In comparison, the Maintenance Personnel Performance Simulation (MAPPS), Crew Chief, and Profile models were developed specifically to model maintainer tasks.

Human Operator Simulator (HOS)

Overview. HOS is a general purpose simulation tool originally developed under U.S. Navy sponsorship for modeling human operators, systems, and the environment (Strieb & Wherry, 1979). HOS was designed to predict system performance and operator workload by a dynamic interactive simulation of the environment, the hardware/software system, and the operator. A family of operator micromodels are available for developing a simulation. The micromodels contain algorithms that predict the timing and accuracy of basic human cognitive-perceptual, communication, and psychomotor actions. The most recent version of HOS, HOS-IV, is implemented in Microsoft C on an IBM PC-AT compatible microcomputer (Harris, Iavecchia, Ross, & Schaffer, 1987; Harris, Iavecchia, & Bittner, 1988). HOS-IV was developed under the sponsorship of the U.S. Army Research Institute for the Behavioral Sciences (ARI).

Description. HOS-IV is a rule-based simulation model that uses knowledge representation techniques to structure the simulation. This "top-down" approach allows the user to design the simulation flow to be independent of the implementation of low-level simulation actions and micromodels. HOS-IV allows the user to simulate the effects of mental fatigue on the other performance micromodels and to add to or modify the existing human

performance micromodels. HOS-IV can simulate the performance of both sequential and concurrent tasks.

Four classes of inputs are required for HOS-IV: (a) descriptions of the system design, (b) procedures for using the system, (c) human operator characteristics, and (d) a mission scenario. During a typical HOS-IV implementation, the analyst first determines the allocation of functions between the human operator and the machine. Following this, the analyst describes the environment, the hardware system, and the operator procedures and tactics for interacting with the system and for accomplishing mission goals.

The execution of HOS-IV results in a sequence of temporal operator decisions on the basis of moment-to-moment mission events and predefined tactics and procedures. Once a procedure is selected, HOS-IV micromodels are invoked to perform specific actions (e.g., reading information from a display or manipulating a control). The HOS-IV outputs include (a) a timeline of events for the operator, system, and environment, (b) user-defined measures of effectiveness, and (c) standard analyses, such as action completion time, frequency of actions, time per action, and errors.

HOS-IV simulates a single seated operator who is performing a set of tasks during a mission by observing displays, computing, making decisions, and manipulating controls. HOS-IV is best suited for performing analyses in which the operator's workstation layout is the main concern and where performance degradation results primarily from congestion in reading displays and manipulating controls (Wherry, 1976; Chubb, Laughery, & Pritsker, 1987). Unlike most simulation models, HOS-IV does not sample distributions of performance data; instead, it relies on equations describing relationships between parameters and performance outputs (Meister, 1985).

Microcomputer Systems Analysis of Integrated Networks of Tasks (Micro-SAINT)

Overview. Micro-SAINT is a microcomputer adaptation of the original SAINT (Systems Analysis of Integrated Networks of Tasks) software modeling program developed under the sponsorship of the U.S. Air Force. Micro-SAINT is an extension of the Siegel and Wolf (1969) simulation model. It is used for building and executing task network models, specifically task network models of human operators. Micro-SAINT can be run on an IBM PC-AT compatible microcomputer.

Description. Task network modeling involves the decomposition of system performance into a series of tasks. Each task has associated parameters. For example, tasks may require time, consume resources, present opportunities for errors, or

require interaction with other components of the system. Micro-SAINT permits the modeling of discrete or continuous tasks and single or multiple operator tasks (Laughery & Drews, 1985; Laughery, Drews, Archer, & Kramme, 1986).

The sequencing of tasks is defined by constructing a task network, determining what variables are relevant to the modeling problem, and determining how the variables are affected by tasks in the network (Laughery et al., 1986). The tasks are related to each other by precedence relationships. The precedence relationships (a) specify the flow of tasks through the network and (b) indicate tasks that can be initiated following the completion of previous tasks or other specified conditions. As individual tasks are completed in the network, they can modify later precedence relationships and alter the flow of the network (Meister, 1985).

Each task in a Micro-SAINT task network is associated with other tasks and with input/output parameters that specify the nature of the predecessor tasks, task characteristics, and the logic for branching to other tasks. The time to perform an individual task can be specified in terms of the mean completion time and the expected distribution of performance times. Tasks can be prioritized in terms of their importance to the system mission; thus, less important mission tasks can be skipped if time grows short (Meister, 1985).

The primary outputs of a Micro-SAINT program execution are the time required to perform the tasks in the network each time the model is executed and the distribution of times. In addition, a "snapshop" can be taken at any time during model execution that indicates the value of variables that are associated with the tasks (Laughery et al., 1986).

Sequiturs Workload Analysis System (SWAS)

Overview. SWAS is a computer simulation model, developed under the sponsorship of the Bell Helicopter Company, that provides man-machine system performance predictions and identifies "bottlenecks" that disrupt successful task completion. The bottlenecks include intra- and inter-operator processing difficulties and equipment delays. SWAS also allows the modeler to assess (a) individual differences in operator performance of discrete or continuous tasks performed sequentially or concurrently and (b) the effect of wearing protective clothing. The model possesses characteristics of both network models and production models. SWAS is designed to run on an IBM PC-AT compatible microcomputer (Holley & Parks, 1987).

Description. SWAS contains a simulation executive component that interacts with four principal modules: the Monte Carlo module, the production system module, the individual differences module, and the statistics module. The Monte Carlo module

produces task element performance times from a probability distribution. Adjustments to task element performance times, reflecting intra-operator timesharing, are made by (a) the production system module, which follows concepts described by Wickens' (1984) multiple attentional resources model, and (b) the individual differences module, which makes adjustments on the basis of user-defined runtime variables. The statistics module provides descriptive and inferential statistics about system performance and workload.

SWAS is both a task database management system and a simulation and analysis system. Tasks are selected and organized into task blocks. Task blocks are then merged to build a mission segment file. During this process, codes for continuous tasks, concurrent tasks, and task precedences are assigned. Subsequently, the performance/workload simulation and analysis are conducted.

SWAS produces data about the following parameters:

- the probability that the system can successfully complete the mission segment,
- the relative proportions of time required by human operators versus system equipment to perform mission segments,
- distributions of workload across the system, and
- bottlenecks resulting from task timesharing overloads or delays caused by waiting for other operators.

Task Analysis and Workload (TAWL)

Overview. TAWL comprises a series of related models for predicting operator workload in current and emerging Army helicopter systems that were developed under the sponsorship of ARIARDA (Aldrich et al., 1988). Baseline workload prediction models were developed for the Army's proposed light helicopter experimental (LHX) (Aldrich, Szabo, & Craddock, 1986), the AH-64A attack helicopter (Szabo & Bierbaum, 1986), and the UH-60A utility helicopter (Bierbaum, Szabo, & Aldrich, 1987). The models permit the user to compare workload estimates for a baseline system with workload estimates for the same system with an alternate crew configuration or with different automation options. The models are designed to run on an IBM PC-AT compatible microcomputer.

Description. The first step in developing the models is to perform a mission, task, and workload analysis of the aviation system. Data from the analysis are summarized on function analysis worksheets. The worksheets present verb-object task descriptors for each task, identify the crewmember performing each task, and identify the subsystem(s) associated with each task. The worksheets also present numerical ratings of each task's workload components and an estimate of each task's duration. Thus, the function analysis worksheets provide a comprehensive

summary of the information used to establish the data bases for the workload prediction models.

Both discrete and continuous tasks and sequential and concurrent tasks are included in the models. Discrete tasks are further categorized as fixed or random. Mission requirements and conditions determine the duration of concurrent tasks. Estimated task performance times are obtained either directly from observations of pilot performance in a procedures trainer or indirectly from subject matter expert judgments.

Workload is defined as the total attentional demand placed on the operators as they perform the mission tasks. Consistent with Wickens' (1984) theory that workload is a multidimensional construct, five different workload components (visual, auditory, kinesthetic, cognitive, and psychomotor) are defined for each task. Workload is estimated by using a verbally anchored 7-point rating scale.

The computer models predict total workload experienced in the performance of discrete and continuous tasks using information from the function analysis worksheets. Two types of time-based decision rules are used for building the mission segments from the task data base. First, function decision rules specify the sequence and time for the performance of each task within each function. Second, segment decision rules specify the sequence and temporal relationships for combining the functions to form mission segments.

The models use the time-based function and segment decision rules to place the tasks performed by the operator(s) on the mission timeline at appropriate half-second intervals. The models produce estimates of total workload associated with the performance of concurrent and sequential tasks. The total workload for concurrent tasks is computed by summing the workload component ratings assigned during the task analysis. When excessive workload occurs, the specific half-second intervals are identified on the segment timeline by referring to the workload component sums. The models provide diagnostic indexes of excessive operator workload for concurrent tasks and sequences of concurrent tasks.

Research is currently being conducted to establish the reliability of the workload rating scales and to validate (a) the workload parameters used to develop the models and (b) the workload predictions produced by the models. The validation research will be performed through a series of investigations employing part- and full-mission simulation.

Maintenance Personnel Performance Simulation (MAPPS)

Overview. The MAPPS model is a mainframe-level digital computer simulation model of the performance of a nuclear power

plant maintenance technician or a team of technicians. MAPPS was developed under the sponsorship of the Oak Ridge National Laboratory. The model considers personnel, environmental, and motivational variables to yield predictions of the performance quality and required performance time for the simulated nuclear power plant maintenance technicians working alone or as a team (Siegel, Bartter, Wolf, Knee, & Haas, 1984a, 1984b). The model was developed using the results of comprehensive task analyses of maintenance technician and maintenance supervisor positions. During the task analyses, job incumbents rated maintenance tasks on the frequency of task performance, training time and requirements, consequences of inadequate task performance, and cognitive and perceptual-motor ability requirements.

Description. Four types of input data are provided for each simulated maintenance task: conditions of work, characteristics of maintenance technician(s), task information, and subtask information. Task information consists of data describing the complete task. Subtask information describes the characteristics of each subtask involved in task completion. The input data can be varied by the individual type of task or in any combination of the four types of input data.

During the simulation of a subtask, the effects of the following variables may be considered:

- difference between the required cognitive and perceptual-motor abilities and the actual cognitive and perceptual-motor abilities of the maintenance technician;
- technician fatigue or fatigue relief resulting from rest breaks;
- time since last task performance;
- stress induced by faulty communication, differences between required and actual abilities, insufficient time, or radiation;
- technician level of aspiration;
- supervisor's performance expectation;
- quality of written support procedures;
- difference between required and actual manning level;
- performance decrement due to high environmental temperature;
- equipment accessibility; and
- organizational climate and error detection.

The variables interact with the model in accordance with specified rules of logic (e.g., an increase in stress results in an increase in errors) and functional relationships based on the human performance literature. The model can also simulate the performance of troubleshooting, decision making, and the donning and doffing of protective garments.

As a simulation is being conducted, it is possible to allow the simulated maintenance technician or team to skip a nonessential subtask under high stress levels. It is also possible to repeat the simulation of a subtask, loop ahead or back in a subtask sequence, or branch into a new subtask sequence following subtask failure. The simulated procedures continue serially until the subtasks constituting a task are completed. Typically, a number of full-task simulations are run to smooth random effects.

The MAPPS model produces a variety of human performance information, including quantitative technician performance data, areas of success and failure, performance times, detected and undetected errors, and stress levels. The analytical results can be provided at several levels of detail as specified by the user. The results are also available in summary form.

Crew Chief

Overview. Crew Chief is a CAD model that allows the equipment designer to simulate the physical characteristics and limitations of an aircraft maintenance technician. The model allows the designer to simulate a maintenance activity on a computer-generated image of an aircraft design and to determine if the required maintenance activity is feasible. Crew Chief is actually an expert system that allows the designer to perform the functions of an expert ergonomist detecting and correcting design-related maintainability deficiencies on the spot prior to the development of a hardware mock-up (McDaniel, 1988; McDaniel & Askren, 1985).

Crew Chief was developed to alleviate maintainability problems usually created if the designer lacks the following information:

- feedback about previous maintainability problems,
- three-dimensional representations that allow visualization and analysis of equipment accessibility for maintenance tasks,
- experience with ergonomics and statistics, and
- applicable ergonomics data in a useable and understandable format.

The model was developed jointly by the U.S. Air Force Aerospace Medical Research Laboratory and the U.S. Air Force Human Resources Laboratory at Wright-Patterson Air Force Base, Ohio, as a tool for evaluating the maintainability of Air Force aircraft. It is an outgrowth of the Computerized Biomechanical Man Model (COMBIMAN). Crew Chief was designed to interface with the three most popular three-dimensional CAD systems used by aerospace manufacturers. Depending on the CAD system used, Crew Chief requires either a mainframe computer or an engineering workstation computer.

Description. The input for Crew Chief consists of the graphic representations of a system contained in a CAD data base. Crew Chief is able to access extensive anthropometric data bases containing information about the physical characteristics and limitations of the maintenance technician. The model can graphically represent the following physical characteristics of the maintenance technician and work environment:

- correct body size and properties for male and female maintenance technicians,
- encumbrance of clothing and personal protective equipment,
- physical strength and mobility limitations for simulated working postures,
- physical access for reaching into confined areas,
- visual access for direct and indirect viewing, and
- human strength capability for hand tool usage and manual materials handling tasks.

Crew Chief can also handle interactions of these characteristics. For example, a Crew Chief simulation may show that, although a maintenance technician can access the head of a bolt with a wrench, he or she is unable to apply enough torque to loosen the bolt because of space and mobility limitations.

The model can simulate several common work activities, such as raising, lowering, carrying, holding, positioning, reaching, moving, turning, grasping, gripping, inspecting, pushing, and pulling. In addition, Crew Chief can model the following common hand tools: screwdrivers, socket wrenches, pliers, hammers, chisels, saws, wrenches, drills, riveters, files, and scrapers.

Crew Chief is currently being expanded in two different areas. First, work is under way to incorporate standard elemental task performance times from time-motion data bases into the model to provide the designer with the time estimations for removal and replacement of aircraft components. This will allow the designer to consider variables such as posture, interference, clothing type, and human fatigue when estimating repair time. Second, the user interface is being enhanced so that the model can interact with additional CAD programs (McDaniel, 1988).

Profile

Overview. Profile is a generic expert system model of troubleshooting performance that can be applied to several types of equipment. The model was developed under the sponsorship of the Office of Naval Research. Profile simulates the diagnosis of sample system failures and generates a testing sequence for each sample failure that is representative of the testing that would be performed by a qualified technician. The objective of the diagnostic strategy employed is to minimize a combined function of repair time and consumption of spare parts. The model is intended

to help the designer determine the maintainability implications of a wide range of equipment design alternatives, including packaging, modularization, test point provisions, front panel design, and the extent of automated test facilities (Towne, 1984; Towne & Johnson, 1987; Towne, Johnson, & Bond, 1988). The application of Profile requires a mainframe computer.

Description. The model is organized as a highly structured set of generic troubleshooting rules and associated metrics computed by specialized functions. The rules and metrics are the result of extensive experimental observations of human diagnostic performance and studies of different diagnostic strategies. The model generates a detailed sequence of testing actions consisting of test selection, test performance, and test interpretation that are required to isolate a fault. Standard times for individual maintenance actions are summed to provide a total time to diagnose and repair an item. This is repeated for a large sample of representative failures to obtain a distribution of corrective maintenance times. This distribution represents the probable corrective maintenance time required by the system design and the maintenance conditions.

Profile is configured to produce near optimal fault isolation sequences, and thus simulates the performance of expert technicians when provided with perfect fault-effect data. However, a system that is easily maintained by highly skilled technicians may result in unacceptably long repair times and high error rates when only maintenance technicians with average skills and limited experience are available. Therefore, the model can be configured to simulate the performance of a more typical technician population when provided with degraded fault-effect data. In this manner, the Profile model can predict how differences in skills and experience may affect troubleshooting performance.

Four specific types of information are required to exercise the Profile model for a particular system:

- a list of the replaceable units and their interconnections;
- a list of possible test points and indicators;
- the disassembly sequences required to gain access to internal parts and test points; and
- the physical groupings of components into modules, boards, units, etc.

When the Profile model is exercised, the following summary data are provided to the user:

- the mean time to repair and the distribution of repair times;
- an analysis of the usefulness of all indicators and test points, thus highlighting maintenance features that are redundant or of marginal value;

- an analysis of false replacements, indicating those components that are likely to be consumed in quantities greater than their failure rates would indicate;
- an identification of additional indicators and test points needed to discriminate between parts that produce identical symptoms under the current design;
- a summary of the types and frequencies of maintenance actions required to resolve a sample of faults; and
- the proportion of time spent performing the maintenance actions.

In addition to evaluating the maintainability characteristics of a system design, Profile may be useful for (a) supporting an intelligent (i.e., individualized) maintenance training system, (b) generating fault isolation strategies, and (c) determining the maintenance time required by various repair policies (Towne et al., 1988).

In summary, Profile was designed to generate troubleshooting behaviors very similar to those of qualified technicians working with adequate training, facilities, and time to resolve single, persisting faults. Furthermore, exercising the model can help identify design features that either contribute to maintainer errors (e.g., false replacements) or require higher maintenance technician skill levels. Work was recently completed to integrate Profile with the Mentor-Graphics CAD system (Towne, 1988).

Expert System/CAD Approaches to Maintainability Design

Both Crew Chief and Profile represent initial attempts to combine the features of expert systems and CAD techniques. Both models are most productively applied during the demonstration and validation phase or the full-scale development phase of the materiel acquisition process (Flegler, Permenter, & Malone, 1987). A need exists to develop expert system/CAD techniques that can be used earlier in the design process and that can help improve the quality of trade-off decisions required during the design of aviation systems.

The Logistics and Human Factors Division of the U.S. Air Force Human Resources Laboratory at Wright-Patterson Air Force Base, Ohio, is currently sponsoring exploratory research to develop analytical models, computer software, data bases, and work procedures that include maintenance and logistics factors in the computer-aided design of aviation systems. The objectives of this research are to understand the systems engineering process, including design trade-off decisions, and to improve the supportability that is designed into aviation systems. One of the more promising areas is the integration of computer-aided maintainability analysis with CAD (Potempa & Gentner, 1988).

The expected benefits of this research are (a) a more efficient design process, (b) more explicit trade-offs during system design, and (c) better reliability and maintainability analysis techniques that can be implemented throughout the stages of systems acquisition when critical design decisions are made (Department of the Air Force, 1988). This research appears to have great potential benefit for improving the maintainability design of Army aviation systems and should be closely monitored.

Section IV: Discussion and Recommendations

Section IV consists of six subsections. The first two subsections discuss and compare the utility of the three comparability methodologies and the seven behavioral simulation models for improving the maintainability design of emerging Army aviation systems. The third subsection discusses the need for a comprehensive methodology or model of Army aviation maintainer performance and proposes a set of evaluation criteria. The fourth subsection presents the conclusions drawn from the comparison of the comparability methodologies and behavioral simulation models. The fifth subsection suggests three maintainability research tasks that can be addressed in the future. The final subsection summarizes the overall findings of the research.

Critique of the Comparability Methodologies

The three comparability methodologies discussed in Section III provide the means for estimating the logistic support or manpower, personnel, and training requirements of a proposed system if comparable systems or system components exist. Many new systems do evolve from existing systems or system components (U.S. Air Force Systems Command, 1988). Therefore, the three comparability methodologies have some utility for the design of evolutionary systems. Of the three methodologies reviewed, the ASSET methodology with its maintainability-related analytical procedures (i.e., the Integrated Task Analysis Procedure, the Maintenance Action Network Procedure, and the Design Option Decision Tree Procedure) and its Reliability and Maintainability computer model appears to have the most utility for addressing specific maintainability issues.

However, comparability methodologies have three disadvantages that limit their utility for improving maintainability design. First, exercising the methodologies produces little direct insight about specific design features that will improve maintainability. This is particularly true when the emerging system concept differs significantly from existing systems. Second, comparative methodologies tend to perpetuate (a) poor maintainability design features and (b) poor personnel and training practices associated with existing systems. Third, comparability methodologies rely heavily on expert judgment and are very time consuming and labor intensive.

Critique of the Behavioral Simulation Models

Both operator and maintainer behavioral simulation models were reviewed as part of this research. As noted in Section I, models developed specifically to simulate operator performance and to predict operator workload were reviewed to assess the extent to which they might be useful for (a) simulating certain aspects of

maintainer performance and (b) predicting maintainer workload and its effect on maintainer performance.

System Maintenance Versus System Operation

System maintenance differs from system operation in many important ways. Table 6 presents a list of task, performance, and situational characteristics of aviation system maintenance and compares them with system operation. It is reasonable to expect that the utility of a model for improving maintainability design will depend on the extent to which it addresses these characteristics. Differences between system maintenance and system operation are discussed in the paragraphs that follow.

Maintainer tasks usually are initiated by a system failure, are discrete and sequential, and are seldom performed concurrently with other tasks. In comparison, operator tasks are usually initiated by the mission events, can be discrete or continuous, and can be performed sequentially or concurrently with other tasks (Drury, Paramore, Van Cott, Grey, & Corlett, 1987). Problem solving plays a more important role in system maintenance than in system operation (Hornick, Robinson, Rogers, & Sullivan, 1981; Malone, 1975). In comparison to system operation, system maintenance typically involves a greater variability of environmental conditions (e.g., temperature, illumination), required workspace, and required working postures. Maintenance usually has more stringent requirements for physical accessibility, physical strength, mobility, and tool manipulation. (McDaniel & Askren, 1985).

The components of workload and the factors that contribute to workload are somewhat different for maintainers than operators. Majoros (1988) noted that aircraft maintenance is usually performed in time-pressured environments in which the maintainer must rapidly and accurately solve complicated fault-isolation problems and repair problems, often while in an awkward physical posture. Therefore, he suggests that maintainer workload results from the interaction of cognitive and physical task requirements, especially when the tasks are cognitively complex, novel or infrequently performed. In addition to the cognitive and physical requirements proposed by Majoros, it is likely that maintainer workload also results from visual and kinesthetic task requirements. In comparison, operator workload models generally assume that operator workload results from the combined effects of visual, auditory, kinesthetic, cognitive, and psychomotor attentional demands that accumulate across concurrently performed tasks, particularly when the time required to perform the task exceeds the time available (Aldrich et al., 1988; Lysaght et al., 1988).

Table 6

Comparison of System Maintenance and System Operation Characteristics

Characteristic	Maintenance	Operation
Task Initiator	System Failure	Mission Events
Types of Tasks	Mostly Discrete	Discrete, Continuous
Temporal Attributes of Tasks	Often Sequential, Seldom Concurrent	Sequential, Concurrent
Problem Solving Requirements	Moderate - High	Low - Moderate
Environmental Conditions	Highly Varied	Relatively Constant
Required Workspace	Large	Small
Required Postures	Highly Varied	Relatively Constant
Physical Accessibility Requirements	Moderate - High	Low - Moderate
Visual Accessibility Requirements	Moderate - High	Moderate - High
Physical Strength Requirements	Moderate - High	Low - Moderate
Mobility Requirements	Moderate - High	Low - Moderate
Tool Manipulation Requirements	Moderate - High	Low
Workload Components	Visual, Kinesthetic, Cognitive, Physical	Visual, Auditory, Kinesthetic, Cognitive, Psychomotor
Contributors to Workload	Time Pressure	Concurrent Tasks

Utility of the Operator Models

Four of the seven models reviewed (HOS-IV, Micro-SAINT, SWAS, and TAWL) were developed specifically to model the characteristics of operator performance and to predict operator workload. They have proven to be useful for this purpose. However, all the models lack the mechanisms for assessing the effects of most of the characteristics of system maintenance listed in Table 6. In addition, each of these models has specific deficiencies for modeling maintainer performance and assessing maintainer workload that further limit its utility.

For example, HOS-IV is limited to modeling a single, seated operator in a fixed workstation. Characteristics of many maintainer tasks (i.e., tasks requiring coordination between multiple technicians or mobility) cannot be simulated. The model represents human operator activity as a discrete, rather than continuous process, and is limited in its ability to account for the effects of individual differences in training or skill levels of maintenance technicians. In addition, HOS-IV assumes that the operator carries out instructions without omitting a step or making any incorrect decisions (Meister, 1985). This makes it impossible to simulate the effects of maintainer errors on a proposed design.

Micro-SAINT was developed as a general system for modeling discrete or continuous networks of tasks. It can model sequential and concurrent tasks involving single or multiple operators but cannot model within-operator differences in task performance. The user is required to supply human performance data to the Micro-SAINT model. For example, a recent implementation of Micro-SAINT, the Workload Analysis Aid (Fontenelle & Laughery, 1988), produces task workload estimates using benchmark rating scales developed by McCracken and Aldrich (1984).

Both SWAS and TAWL allow the modeler to simulate the performance of discrete or continuous tasks performed sequentially or concurrently. Both can accommodate multiple operators and can access elemental task performance times. SWAS combines characteristics of network models and rule-based production systems and can simulate the effects of individual differences on performance. TAWL contains procedures for conducting systematic mission, task, and workload analysis procedures but cannot simulate the effects of individual differences on performance. Neither model addresses the specific components or effects of maintainer workload on performance.

Utility of the Maintainer Models

The MAPPS, Crew Chief, and Profile models were developed specifically to model certain aspects of maintainer performance and therefore address more of the maintainer characteristics

listed in Table 6 than do the operator models. MAPPS was developed to simulate the performance of a nuclear power plant maintenance technician or team of technicians and can simulate the effect of several variables that affect maintenance performance in that work environment. Many of the task, personnel, and environmental variables considered by MAPPS (e.g., fatigue, time stress, quality of written procedures, equipment accessibility) are common to the aviation maintenance environment. For these reasons, the MAPPS model should be evaluated further to determine (a) the similarity between maintenance tasks and working conditions in a nuclear power plant and those in an Army aviation environment, and (b) the extent to which the MAPPS model can be used to assess the maintainability implications of Army aviation system and equipment design.

Crew Chief and Profile simulate the types of maintenance activities that historically have consumed the largest percentage of maintainers' time. Crew Chief was developed specifically to simulate the physical activities required for an aviation maintenance technician to access, remove, and replace equipment. Profile was developed as a generic simulation of fault diagnosis performance and can simulate the fault diagnosis and trouble-shooting activities required to maintain aviation systems. Both Crew Chief and Profile have been designed to interface directly with commercial mainframe or graphics workstation CAD programs currently used by the major aerospace manufacturers.

Proposed Criteria For A Methodology or Model For Improving Maintainability Design

The literature review failed to reveal a comprehensive methodology or model of maintainer performance and workload that can be used to predict maintainability during the early stages of Army aviation system development. One reason for this shortcoming is the lack of a validated set of criteria that can be used to guide the development of a methodology or model and to evaluate the methodology's or model's utility. The author suggests that, at a minimum, a methodology or model should meet the 10 general criteria listed in Table 7. The criteria were developed after considering the (a) results of the maintenance and maintainability design literature reviewed and discussed in Section II and (b) the characteristics of system maintenance listed in Table 6. The criteria were derived primarily from Bond, 1987; Crawford and Altman, 1972; Cunningham and Cox, 1972; McDaniel and Askren, 1985; Smith et al., 1970; and Towne et al., 1988.

Table 8 summarizes a preliminary assessment of the extent to which the methodologies and models reviewed and discussed in this report meet the 10 criteria. An "X" indicates that the methodology or model was judged to meet the criterion to at least a

Table 7

Proposed Evaluation Criteria for a Methodology or Model For Improving Maintainability Design

1. Does the methodology or model address the (a) types of maintenance tasks, (b) physical strength, postural, mobility, and tool manipulation requirements, and (c) variety of working conditions encountered in Army aviation maintenance?

2. Does the methodology or model address the physical and visual access requirements of a system or equipment?

3. Does the methodology or model address the fault diagnosis (troubleshooting) requirements of a system or equipment?

4. Does the methodology or model predict maintenance time and errors at different maintenance levels (i.e., AVUM, AVIM, depot)?

5. Does the methodology or model predict the effects of individual differences in maintainer skills and experience on system maintainability?

6. Does the methodology or model predict the maintainability of qualitatively different types of systems (e.g., fixed wing vs. helicopters) and equipment (e.g., electronic vs. mechanical)?

7. Can the methodology or model automatically apply valid maintainability design guidelines to a proposed system or equipment at appropriate times during the system design process?

8. Does the methodology or model account for the components of maintainer workload and their effect on maintainer performance?

9. Are the hardware and software required to exercise the methodology or model readily available to the intended user?

10. Will the methodology or model be accepted and utilized by designers of Army aviation systems and equipment?

Table 8

Comparison of the Methodologies and Models on the Proposed Evaluation Criteria

	LSA	HARDMAN	ASSET	HOS-IV	Micro-SAINT	SWAS	TAWL	MAPPS	Crew Chief	Profile
1. Coverage of Maintenance Tasks and Environments	?	?	?	--	--	--	--	?	X	?
2. Assessment of System/Equipment Accessibility	--	--	?	--	--	--	--	?	X	?
3. Assessment of Fault Diagnosis Requirements	?	?	X	--	--	--	--	?	--	X
4. Time/Error Prediction at all Three Maintenance Levels	--	--	--	--	--	--	--	--	?	?
5. Effects of Differences in Maintainer Skills/ Experiences	--	--	--	--	?	?	--	X	X	X
6. Maintainability of Different Systems/ Equipment	--	--	--	--	--	--	--	--	X	X
7. Application of Maintainability Design Guidelines	--	--	--	--	--	--	--	--	X	?
8. Effects of Maintainer Workload on Performance	--	--	--	--	--	--	--	?	--	--
8. Availability of Required Hardware/ Software	?	?	?	X	X	X	X	?	?	?
10. Acceptable to System and Equipment Designers	?	?	?	X	X	X	X	?	X	X

KEY: X = Meets criterion to at least a moderate extent; ? = Meets criterion to a limited extent;
-- = Does not meet criterion.

moderate extent. A question mark (?) indicates that the methodology or model was judged to meet the criterion, but only to a limited extent. A dash (--) indicates that the methodology or model was judged not to meet the criterion. As Table 8 indicates, only Crew Chief and Profile come close to meeting all of the evaluation criteria. In their present form, each of the methodologies or models is deficient in some respect.

The proposed criteria are not intended to be exhaustive or definitive. However, it is hoped that they will (a) provide a helpful start toward the development of more complete, more specific, and perhaps eventually, quantitative criteria for evaluating the utility of maintainability design methodologies or models, and (b) encourage future research efforts to develop a comprehensive maintainer model that can be used to improve the maintainability design of emerging Army aviation systems.

Conclusions

Of the methodologies and models reviewed, the Crew Chief and Profile models were judged to have the greatest potential for improving maintainability design. Crew Chief can be used by the designer (a) to simulate a physical maintenance activity (e.g., accessing, removing and replacing a component) on a computer-generated drawing of an aircraft system and (b) to estimate if the proposed activity is feasible, given the physical characteristics of the target maintainer population. Profile can be used by the designer (a) to simulate the fault diagnosis and troubleshooting performance of maintenance technicians with the diagnostic skills expected in the target maintainer population and (b) to estimate if a specific design will result in an unacceptably high repair time or number of false replacements.

Therefore, it is recommended that primary emphasis should be placed on evaluating the Crew Chief and Profile maintainer models to determine their appropriateness for improving the maintainability design of emerging Army aviation systems. The evaluations should consist of (a) conducting working sessions with personnel who have developed or have an intimate knowledge of the models, (b) exercising the models to simulate representative Army aviation maintenance tasks and comparing the models' predictions with actual maintenance performance data, and (c) conducting working sessions with equipment designers who use the models to assess the maintainability aspects of their system and equipment designs.

Secondary emphasis should be placed on evaluating the MAPPS maintainer model and the HOS-IV, Micro-SAINT, SWAS, and TAWL operator models to determine if it is both feasible and desirable to modify them to apply to Army aviation maintainer tasks. It is inappropriate to use the operator models, in their present forms, to simulate maintainer performance and to predict maintainer workload. The utility of the comparability methodologies for

these purposes is severely limited by the deficiencies described previously.

Future Research Needs

As noted in Section I, there has been relatively little research directed toward improving the maintainability design of aviation systems. Most of the past maintainability design research was performed or sponsored by the U.S. Air Force and the U.S. Navy. There is a lack of research directed toward maintenance and maintainability design problems encountered in Army aviation systems. Some of the research findings from the other services may be applied to Army aviation maintenance problems, but there are many problems that cannot be solved by generalizing the results of existing research. Army aviation maintenance is often performed on different types of systems and equipment and in different environments and working conditions than in the Air Force and the Navy. Therefore, a program of maintainability research is needed that will address Army aviation systems, mission requirements, and operational environments.

The following three broad tasks should be addressed in a program of research:

- conduct aviation maintenance task and workload analyses,
- monitor current research and development being conducted by other agencies to develop automated maintainability design aids, and
- review the research literature on troubleshooting performance.

These tasks are discussed in the paragraphs that follow.

Conduct Aviation Maintenance Task and Workload Analyses

Army aviation maintenance tasks are determined by the specific concepts followed during the design of Army aviation systems and equipment. Maintenance tasks that are required because one set of design concepts were followed may impose higher levels of workload than maintenance tasks that would be required if alternative concepts were followed. Thus, estimates of workload can provide useful feedback for maintainability design (Majoros, 1988; Morris & Rouse, 1985).

Little is known about the nature and extent of maintainer workload. As discussed in Section IV, research suggests that maintainer workload may differ qualitatively from operator workload. An improved understanding of the workload components of Army aviation maintenance tasks will help determine how existing operator workload prediction methodologies and models might be modified and applied to maintainability design issues. Such an

understanding can be achieved through a thorough analysis of Army aviation maintenance tasks.

Therefore, it is recommended that maintenance task and workload analyses be conducted for a recently developed and fielded Army aviation system, such as the AH-64A advanced attack helicopter. The AH-64A is the operational Army aircraft whose design best illustrates the most recent maintainability design concepts. In addition, many of the maintenance tasks required for the AH-64A are similar to maintenance tasks required for other Army helicopters, permitting some degree of generalization of the task analysis results to other Army aviation systems.

The task and workload analyses should be conducted for selected tasks and subsystems (e.g., electrical, flight control) at the AVUM and AVIM levels, and, if resources permit, at the depot level. At a minimum, the task analyses should provide data on the following variables (Chapanis & Shafer, 1988; Department of Defense, 1979; Meister, 1985):

- conditions for task initiation,
- equipment acted upon,
- required response(s),
- nature of feedback provided,
- task frequency and duration,
- information and communication requirements,
- evaluations and decisions required of the maintenance technician,
- characteristic errors,
- required tools and job aids,
- workspace and environmental considerations,
- potential work hazards, and
- criteria for satisfactory performance.

The overall objectives of the workload analyses should be:

- to determine the components of maintainer workload and their interaction,
- to determine how existing operator workload analytical techniques and measures might be modified to apply to the maintainer,
- to evaluate the effect of workload on maintainer performance and errors,
- to relate maintainer workload experienced during critical maintenance tasks to system design features, and
- to serve as a precursor to the development of a model of Army aviator maintenance performance and workload.

ARIARDA is currently developing methods and computer models for assessing operator workload in Army aviation systems. Possibly, the operator workload expertise and experience could be

applied directly to maintenance task and workload analyses without additional literature review or an extended period of preparation. If the aviation maintenance task and workload analyses are conducted, preliminary task analysis data should be collected at (a) selected Army aviation AVUM and AVIM units and (b) the Army Aviation Logistics School, Fort Eustis, Virginia. During the visits the researchers should:

- observe maintenance activities and problems in Army aviation maintenance units;
- observe aviation maintenance training (e.g., classroom, part-task trainers, procedures trainers, simulation, and on-aircraft instruction and training); and
- survey the availability and use of job performance aids.

Another source of information that should be considered during the maintenance task and workload analyses are aircraft accident and mishap data from the U.S. Army Safety Center. For example, Schmitt (1983) identified several design features during a systematic evaluation of the Naval Safety Center Accident and Mishap Data Base that contributed to maintainer errors. The information obtained from the visits and the accident and mishap data can provide background material required to perform the task and workload analyses. Furthermore, this information may provide insights about existing Army aviation maintenance problems that could be alleviated through improved systems design.

Monitor Automated Maintainability Design Aid Development

The results of this literature review indicate that there is an immediate need for a comprehensive human factors research program that will identify analytic methods and develop maintainability design tools that can be implemented during the concept exploration phase of emerging aviation system development. Human factors practitioners must learn how to translate their knowledge about the capabilities and limitations of human maintainers into design guidelines or specifications that are meaningful to aviation system and equipment designers.

Little is known about how design engineers integrate different sources of information, particularly human performance information, when making design decisions. As a group, design engineers tend to assume that (a) whatever the characteristics of the system, the human operator and maintainer will be sufficiently flexible to compensate for design deficiencies, and (b) a well engineered system will automatically take into consideration human capabilities and limitations. Experience has demonstrated these assumptions to be inaccurate. It is evident that design engineers typically give a low priority to, or totally ignore, abstract, general, human factors inputs (Meister, 1987).

Therefore, human factors researchers need to develop analytic methods and design aids that will ensure that maintainability enhancing features are incorporated into system design. The development of maintainability design aids will require a better understanding of (a) the content and format of data that system engineers and designers can use and (b) the kinds of information about human capabilities and limitations that design engineers need. For example, research by Meister and Farr (1967), Rogers and Armstrong (1977), and Rogers and Pegden (1977) suggests that designers are more influenced by data presented in quantitative, graphic, or tabular terms than by data that are qualitative and verbal. Meister, Sullivan, Finley, and Askren (1969) found that design engineers are likely to relate certain design concepts and characteristics, such as number and location of test points and troubleshooting procedures, to the skill level of maintenance technicians.

In the future, most aviation system design activities will be performed using CAD systems (McDaniel & Askren, 1985). A methodology or model that directly interfaces with CAD systems and gives the design engineer immediate feedback about the maintainability implications of a specific design is more likely to influence the designer to incorporate maintainability enhancing features. Coppola (1984) proposes that an ideal program for improving maintainability would require the creation of (a) a set of decision rules for incorporating maintainability design features and (b) procedures for trading the maintainability design decision rules off against other system design considerations. Coppola notes that the development of maintainability design decision rules are a near-term possibility, but that a considerable amount of additional work would be required to develop the trade-off procedures.

The Crew Chief and Profile models represent major efforts in developing maintainability design CAD models. Further developments in these models and the current work sponsored by the Air Force to develop expert system/CAD programs for improving maintainability design should be monitored closely.

Review Literature on Troubleshooting Performance

With the possible exception of physically accessing defective equipment, troubleshooting (fault detection and isolation) typically takes up the majority of a maintenance technician's time (see Section II). Therefore, equipment should be designed so that the maintainer with the skill level and experience expected in the field can easily determine the presence, nature, and location of system faults and determine the appropriate course of action (U.S. Air Force Systems Command, 1988). This requires a thorough understanding of the factors that affect troubleshooting performance (Morris & Rouse, 1984).

Although the reliability of BITE has increased somewhat in recent years, a sizable number of military aviation system faults are not accurately detected and isolated by BITE and, therefore, require manual troubleshooting by a maintenance technician (Frederickson, Linquist, & Lehman, 1986). A great deal of research has been conducted to study human troubleshooting performance (e.g., Bond, 1987; Rasmussen & Rouse, 1981) and to incorporate the findings of this research into maintainability design (e.g., Towne et al., 1988). The ultimate goal of this research is to identify design features that minimize troubleshooting time and reduce the probability of false removals and replacements.

Artificial intelligence (AI) technology is playing an increasingly important role in aviation maintenance troubleshooting, most predominantly in the form of expert systems. Expert systems are being evaluated as maintenance job performance aids by the Army, the Air Force, and the Navy. Much of this work was summarized during the Artificial Intelligence in Maintenance Workshop sponsored by the Department of Defense (Richardson et al., 1985). Reis and Thompson (1988) recently described three Army Aviation Systems Command (AVSCOM) programs that are exploring the potential benefit of expert systems for troubleshooting specific aircraft systems on the Army's CH-47D cargo helicopter, AH-1S attack helicopter, and AH-64 advanced attack helicopter. In addition, work is in progress to identify the requirements for (a) allocating maintenance functions between the human maintainer and the expert system and (b) designing the maintainer-expert system interface (e.g., Jonsson, 1988).

Summary

In summary, the Crew Chief and Profile models should be evaluated to determine their utility for improving the maintainability design of Army aviation systems. The MAPPS maintainer model and the HOS-IV, Micro-SAINT, SWAS and TAWL operator models should be evaluated to determine the desirability and feasibility of modifying them (a) to simulate the performance of maintainer tasks not addressed adequately by either the Crew Chief or Profile models and (b) to predict maintainer workload.

In addition, a program of maintainability research should be initiated that will address Army aviation systems, mission requirements, and operational environments. This program should consist of the following activities:

- conducting maintenance task and workload analyses for selected Army aviation systems and equipment as a precursor to the development of a model of Army aviation maintainer performance and workload;
- monitoring research and development efforts to develop expert system/CAD maintainability design models that could apply to Army aviation systems; and

- conducting a comprehensive review of the literature on troubleshooting performance, especially as it applies to Army aviation systems, and monitoring ongoing research and development activities in this area.

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